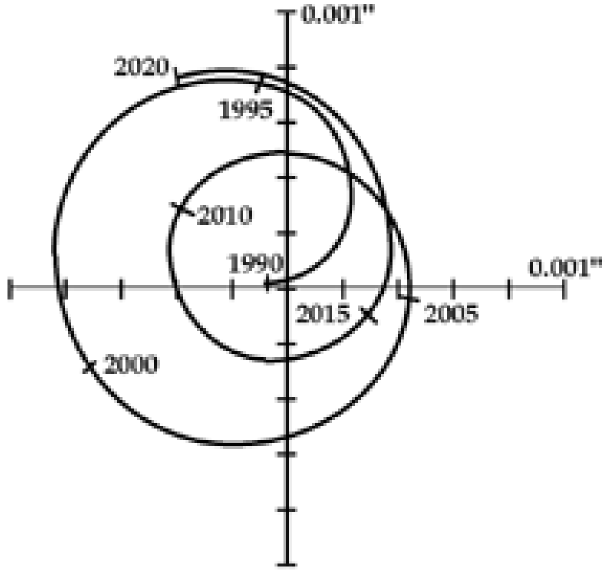


Astrometric Detection of Planets

Michael Shao, JPL

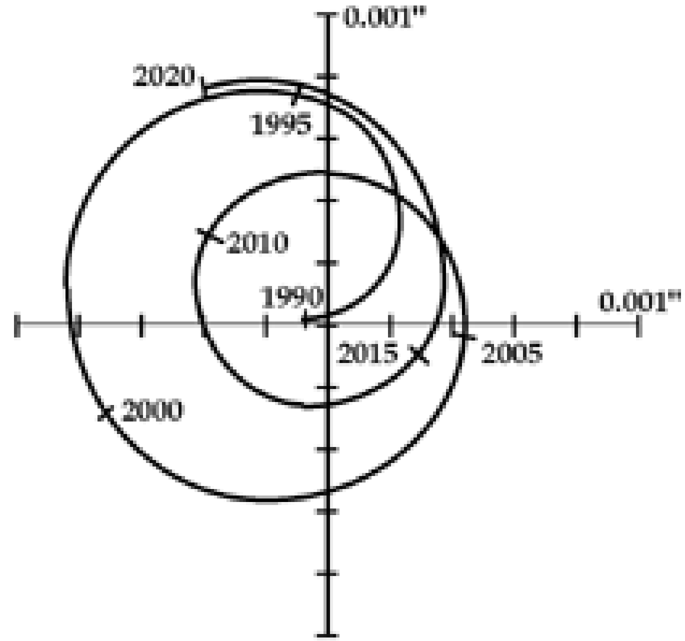
Astrometry

Outline

- *What Astrometry Measures (in planet detection)*
- *Historical Perspective (single telescopes)*
- *Interferometric astrometry (narrow angle)*
  - *Ground based*
  - *Space based*
- *From positions to planets*

The Basic Technique

- *Astrometry looks for the transverse motion of a star caused by orbiting companion(s)*
- *Because astrometry measures the motions in two directions, there is no (sin i) ambiguity*
- *Astrometry is more sensitive to "outer" planets*
- *Size of effect*
  - *Sun-Jupiter 10 pc 0.5 mas*
  - *Sun-Neptune (10 yr) 15 uas*
  - *Sun-Earth 0.3 uas*



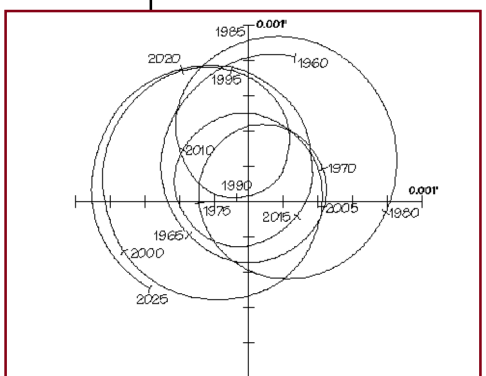
Astrometric Measurements

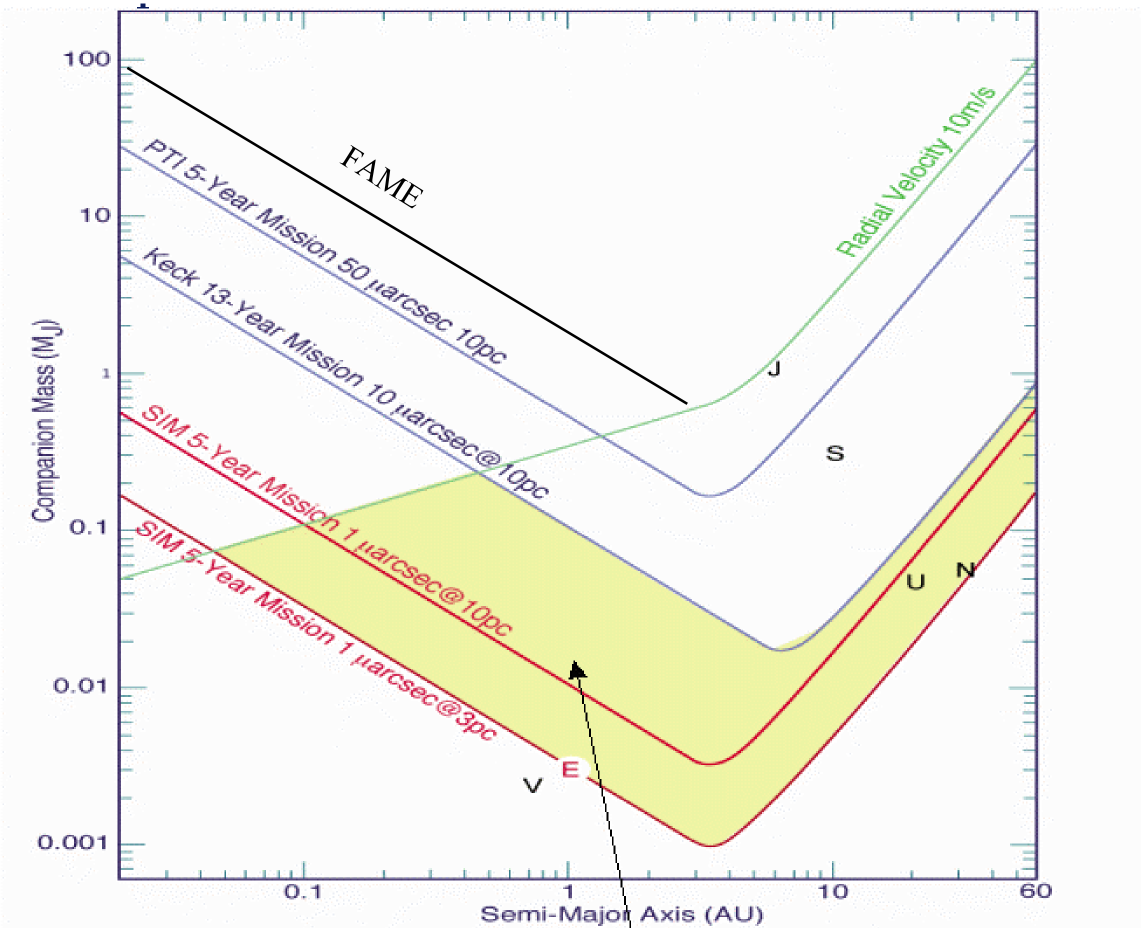
- *Astrometry, by measuring two coordinates of motion of the star due to an orbiting planet, can measure all 7 orbital parameters (if there's enough SNR)*
  - *Mass of the planet (given the mass of the star)*
  - *Semi-major axis, period*
  - *eccentricity, inclination*

Astrometric Planet Detection

Astrometry

Planetary systems inducing only low radial velocities (<~3m/s) in their central star that can't possible to detect from the ground can be detected through the astrometric displacement of the parent star.



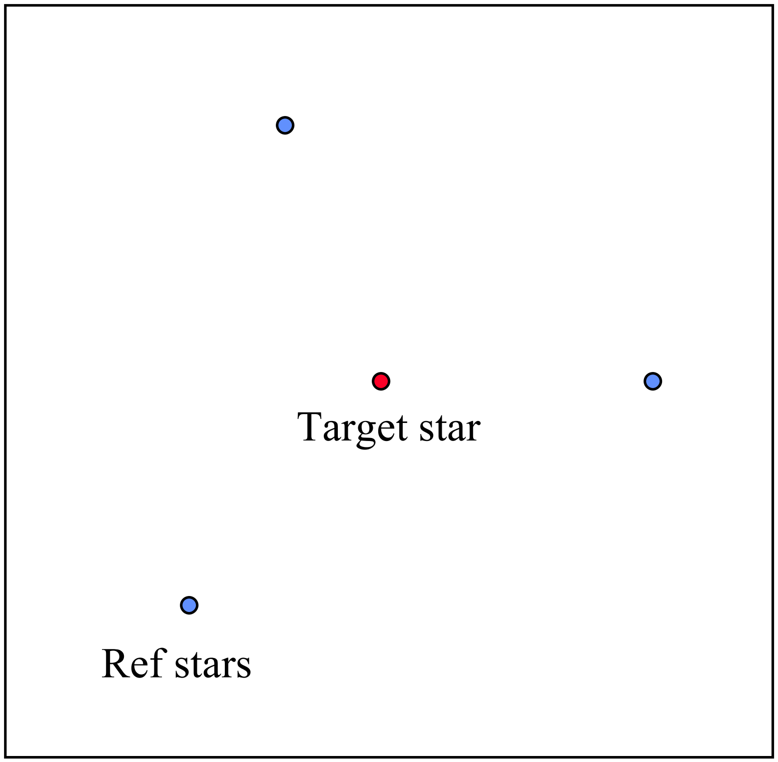


Systems only accessible with SIM

<u>Detection Limits</u>
SIM: 1 μas over 5 years (mission lifetime)
Keck Interferometer: 20 μas over 10 years

Single Telescope Astrometry

Basic technique developed in early 1900's for use with photographic plates



Field of view (MAP Gatewood ~30 arcmin)
(USNO FS ~5 arcmin)
(Keck 2~3 arcmin)

Major Error sources
- focal length change
- tip/tilt of image plane
- rotation of image plane
- non-orthogonal xy axes

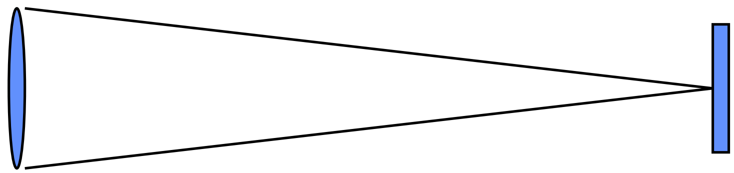
These are corrected using the ref stars

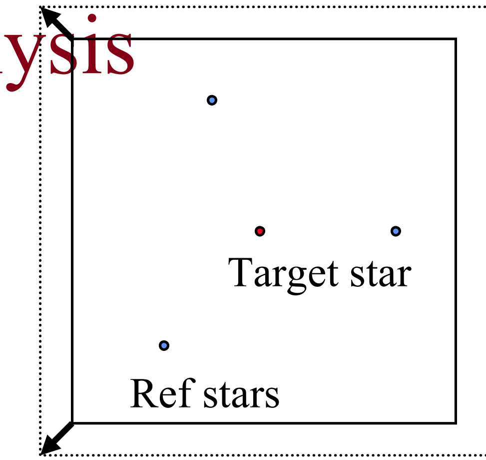
$X' = a + bX + cY$
$Y' = d + eX + fY$

a,b,c,d,e,f solved from ref star coord.

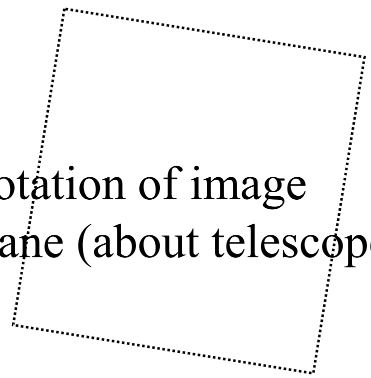
Astrometry

Examples of Error Sources Corrected with standard analysis



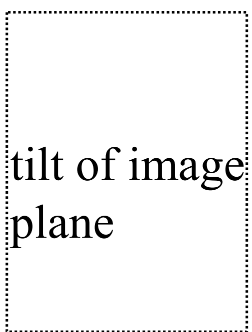


Focal distance change



Rotation of image plane (about telescope axis)

X’= a+bX+cY
Y’=d+eX+fY
A minimum of 3 ref stars are needed



tilt of image plane

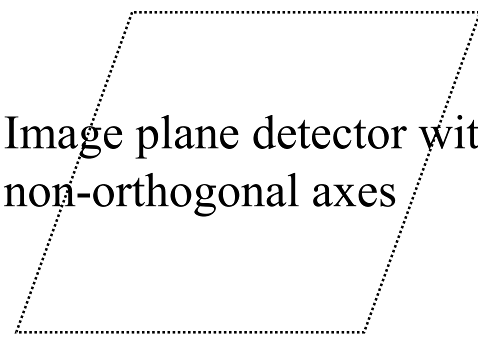
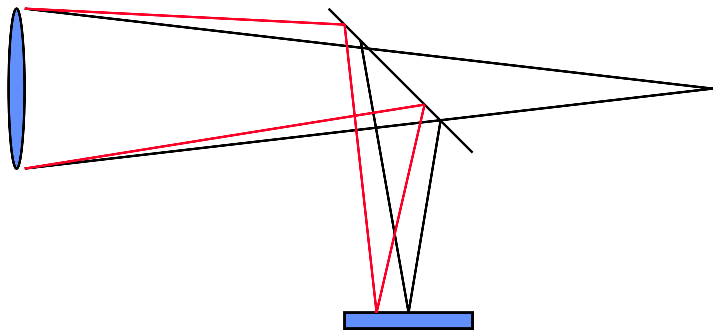


Image plane detector with non-orthogonal axes

Astrometry

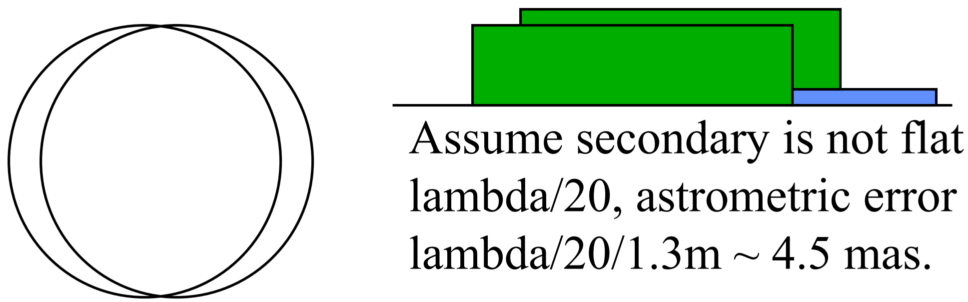
Error sources not modeled



An example of beam walk
In a newtonian telescope
(or any telescope with more than 1 surface)
Different star's light will strike the 2nd-3rd optics at different locations.

We call this beam walk, this wander of the stellar footprint in different parts of the field of view.

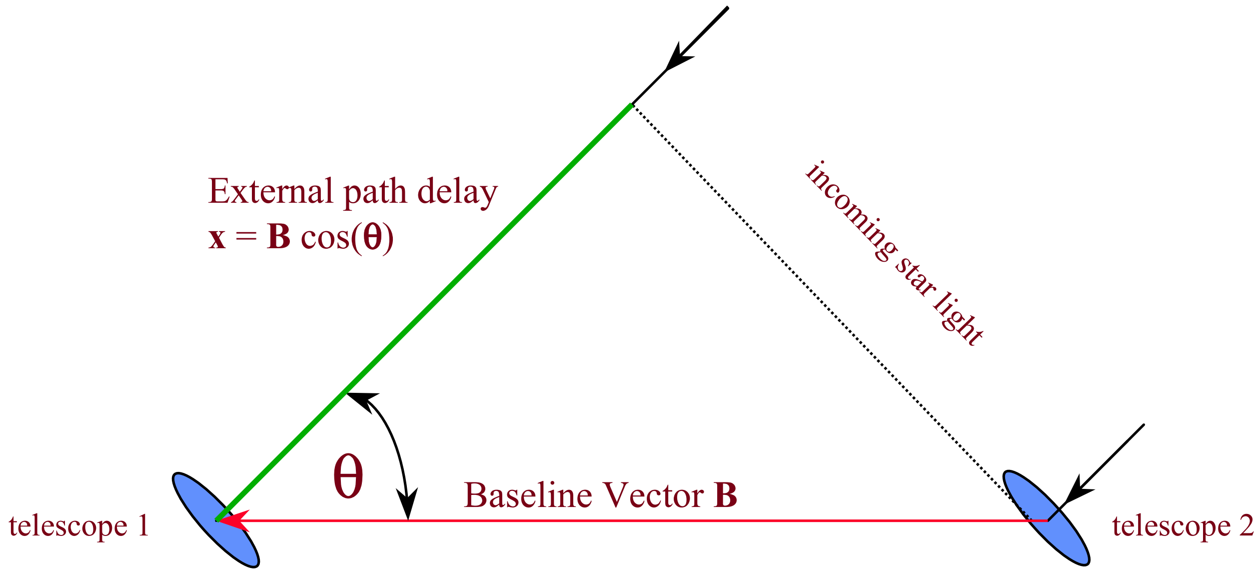
Numerical Example (Keck telescope secondary)
f/15 cass focus ~17m from primary 1.3m footprint moves 5mm, for a star 1 arcmin off axis.



Assume secondary is not flat to lambda/20, astrometric error is lambda/20/1.3m ~ 4.5 mas.

Interferometric Astrometry

*The angle between the star and baseline creates an external path delay **x***

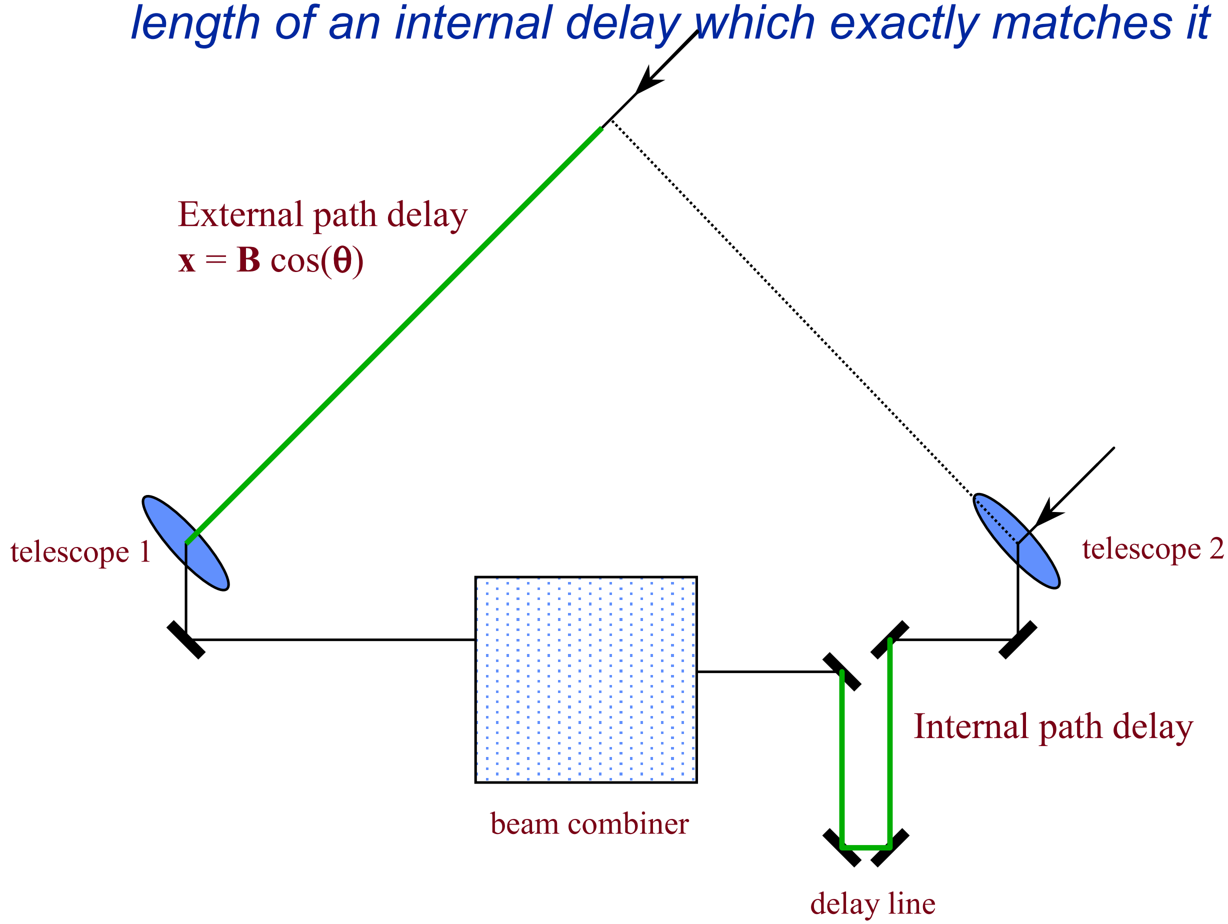


*If we know **B**, and can determine **x**, we can solve for the star position θ*

X=B*S

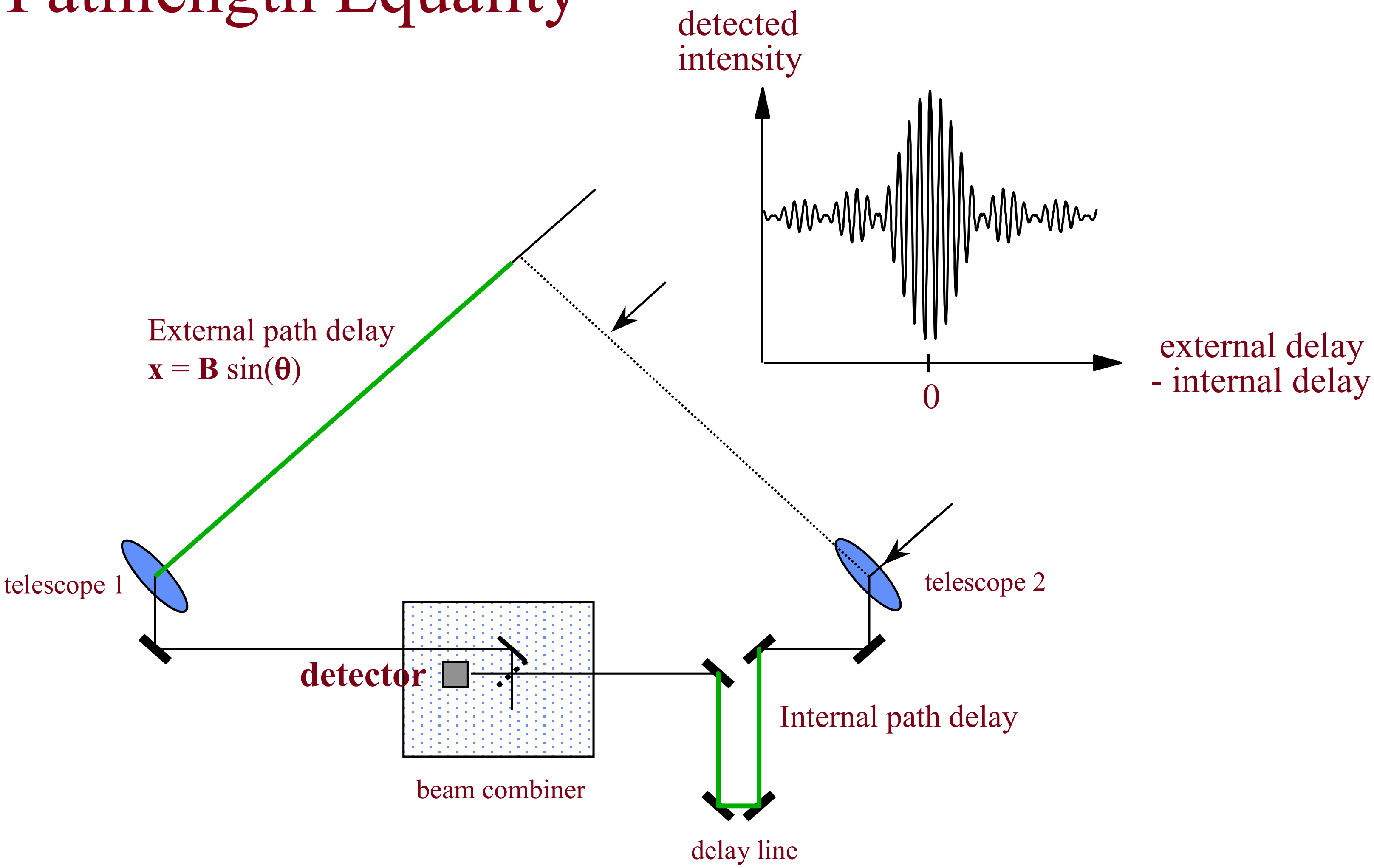
Determining the External Delay

We determine the external delay by measuring the length of an internal delay which exactly matches it



Optical delay lines are used to vary the internal delay

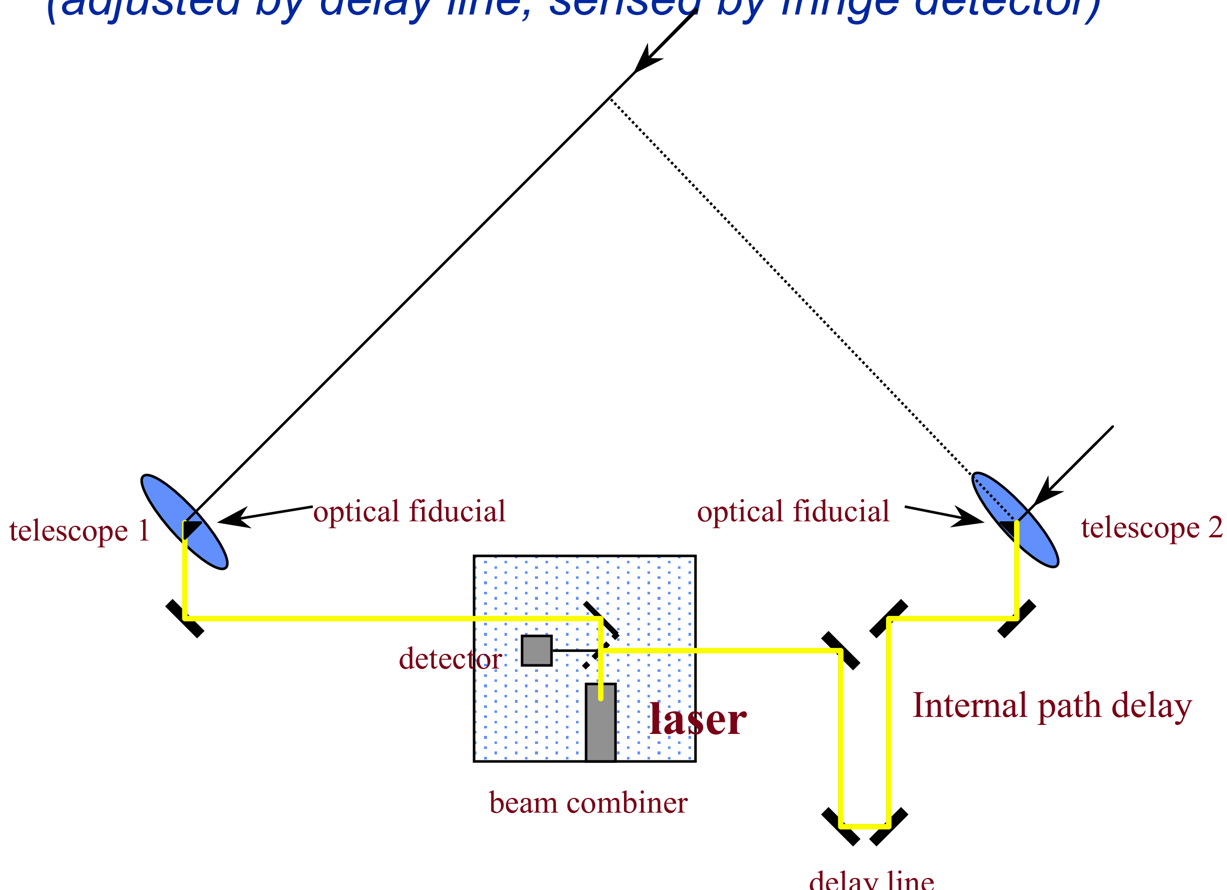
Fringe Position as a Measure of Pathlength Equality



The peak of the interference pattern occurs when the internal path delay equals the external path delay

Internal Metrology

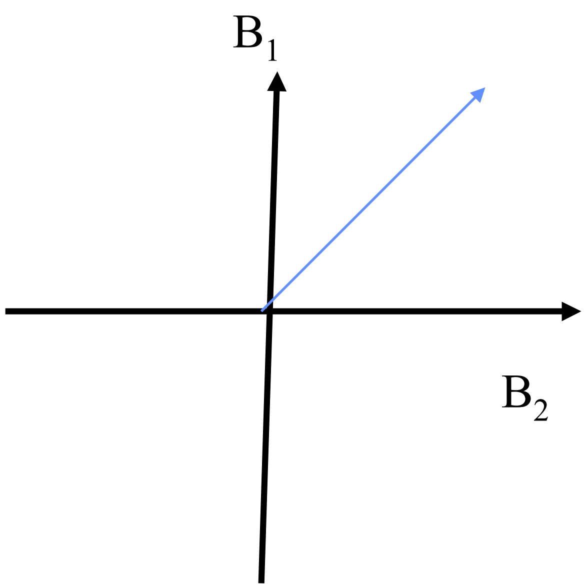
Laser gauge measures internal delay
(adjusted by delay line, sensed by fringe detector)



Laser path retraces starlight path from combiner to telescopes

Fringe Position to Star Position

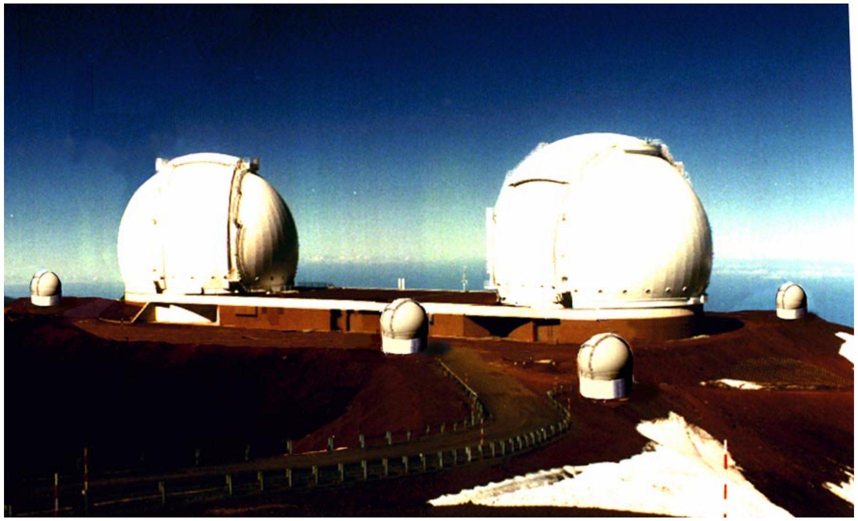
The fringe position (x) is the star position projected on the baseline vector
If we measure the fringe position in two ~orthogonal (and known) baselines we can derive the star's position



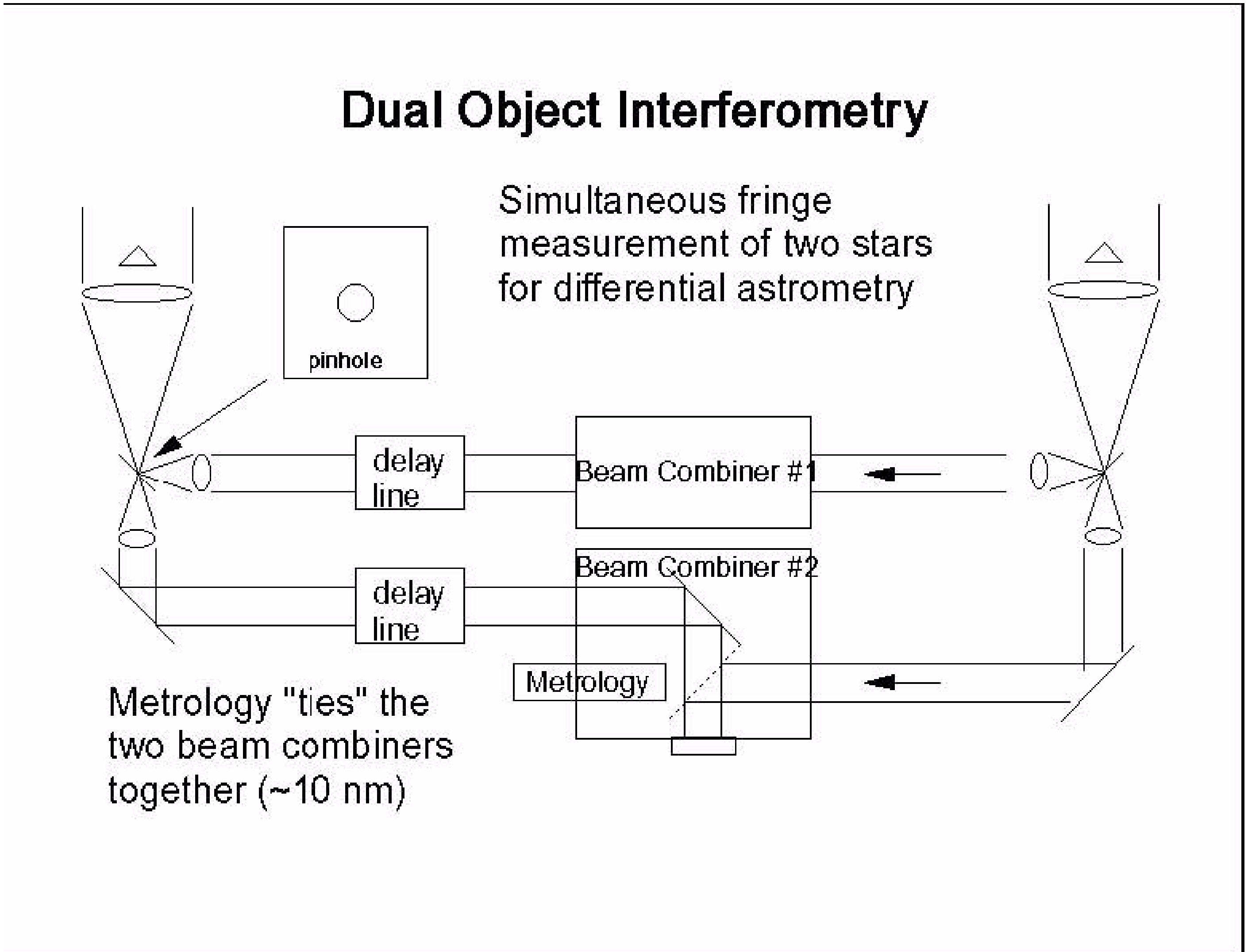
In general the baseline is determined by using the interferometer to observe stars whose positions are known

Ground Based Interferometers

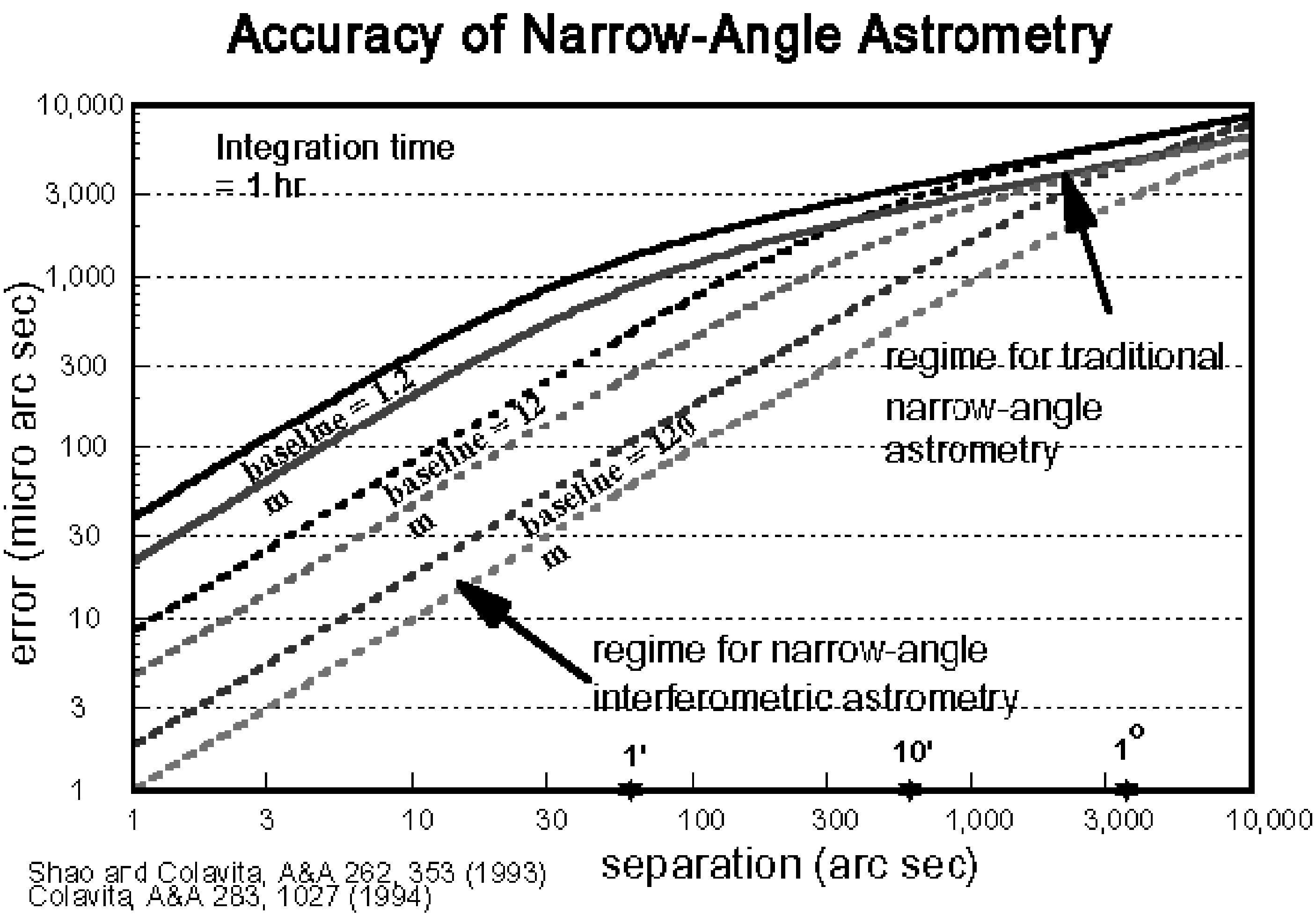
Palomar Testbed Interferometer
Test dual star narrow angle interferometry for Keck



Keck Interferometer with outriggers a-la “Photoshop”

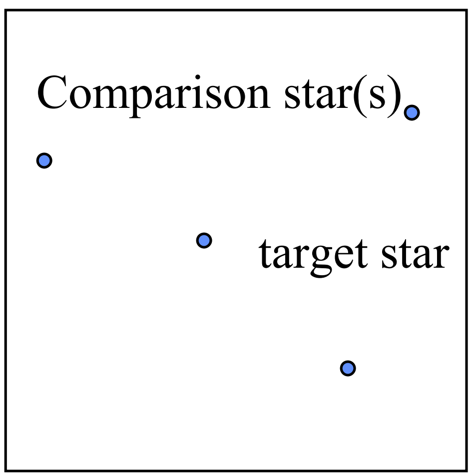

Dual Object Interferometry
Simultaneous fringe measurement of two stars for differential astrometry
pinhole
delay line
Beam Combiner #1
delay line
Beam Combiner #2
Metrology
Metrology "ties" the two beam combiners together (~10 nm)

Ground Based Atmospheric Limits



Measuring the Baseline Vector

- *The basic equation is*
  - *X (fringe position) = B * S +C*
- *We measure the baseline vector B, by looking at the positions of fringes, for 3~5 stars, whose position we know.*
  - *C is calibrated by measuring the position of "nearby" stars*
- *Baseline precision needed for narrow angle astrometry*
  - *Fractional knowledge is desired accuracy/field of view*

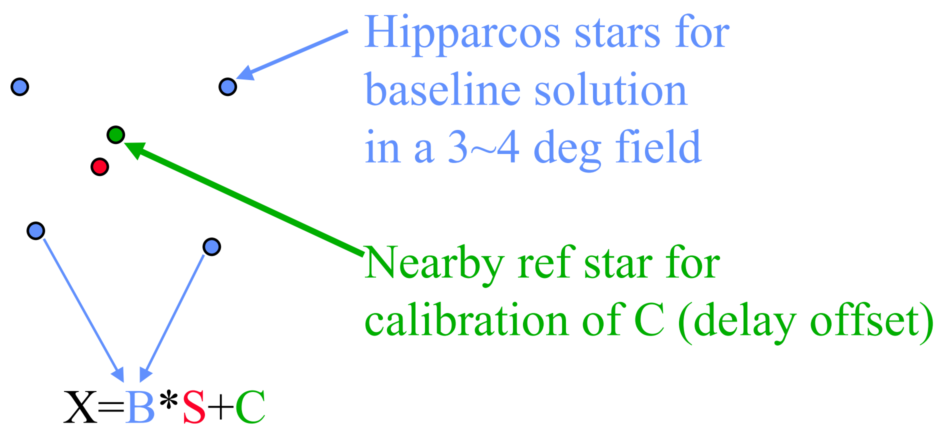


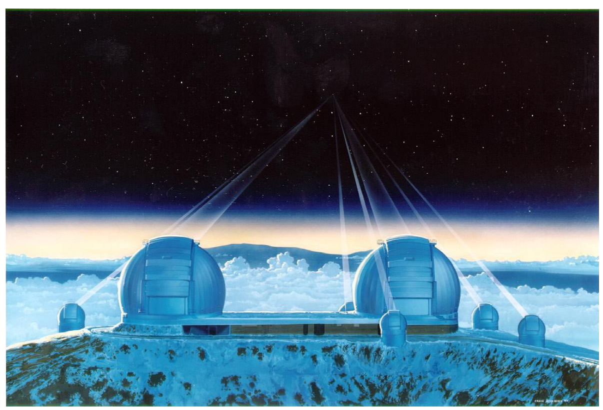
Ground based:
Field ~ 20 arcsec
accuracy ~20 uas
Baseline ~1e-6 length
1 urad direction
Space based: (SIM)
Field ~ 1 deg (3600 arcsec)
Accuracy ~1 uas
Baseline ~ 3e-10
length to 3nm, angle ~60uas

Determining the Baseline
(ground and space)

- *Because of the very narrow field of view, Ground based interferometers only need to know their baselines with 0.1~0.2 arcsec accuracy. (100um baseline lengths) This is easily measured by looking at ~4~5 Hipparcos stars.*
  - *The interferometer baseline must be stable at this level*
- *In space, in the absence of atmospheric turbulence, the potential accuracy is much higher. With that higher accuracy comes unique problems that must be overcome.*
  - *Baseline stability (length ~3nm, orientation ~60uas)*
  - *Astrophysical noise sources*

Baseline Determination (ground)





Baseline vector B must be measured quasi simultaneously with the stellar measurement.

(baseline stable to 0.1 arcsec)

(0.1arcsec*100m = 50um)

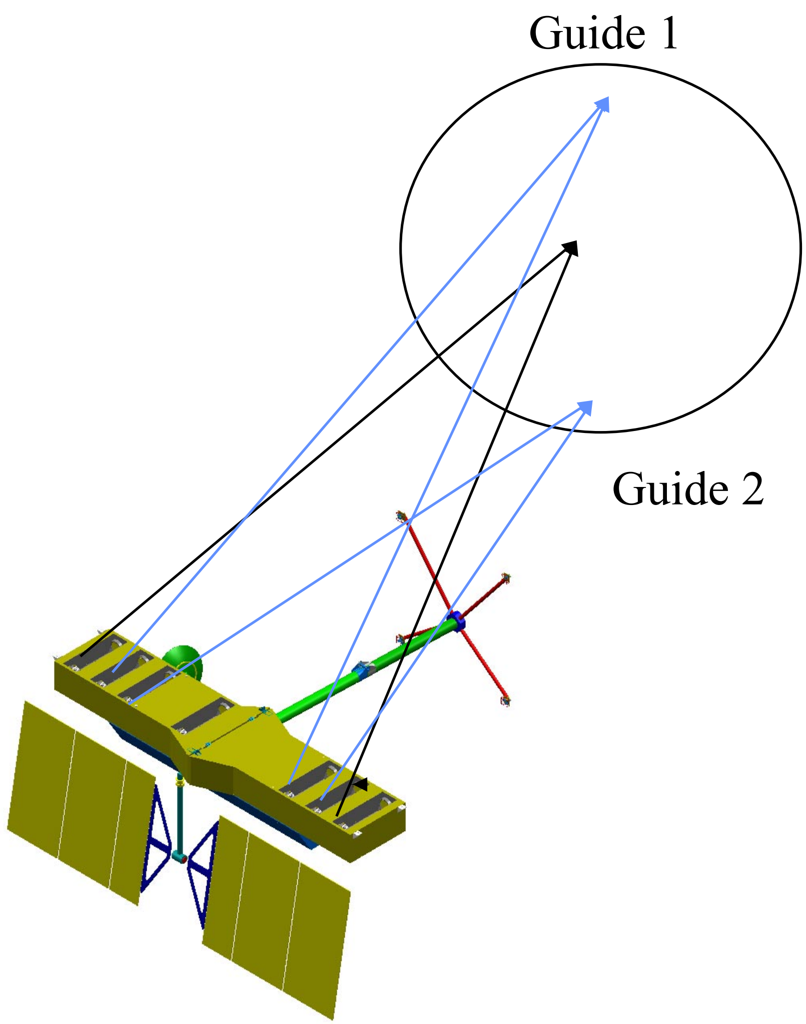
Similarly must measure C on a timescale faster than the drift

20 uas => C stable to 10nm

Baseline determination in Space

- *More complicated than on the ground because the space platform is not intrinsically stable (like Earth rotation)*
- *The only thing with sufficient accuracy to measure the orientation of an interferometer is another interferometer*
- *The steps are:*
  - *1) establish a stable (at the uas) platform*
  - *2) tie the stable platform to the science interferometer*
  - *3) establish the absolute orientation of the baseline*

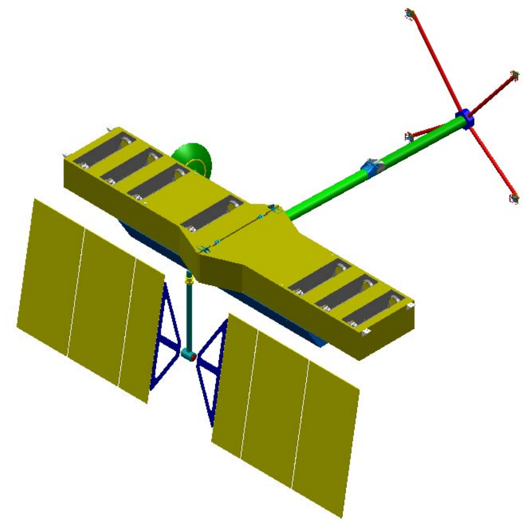
Baseline Determination in Space

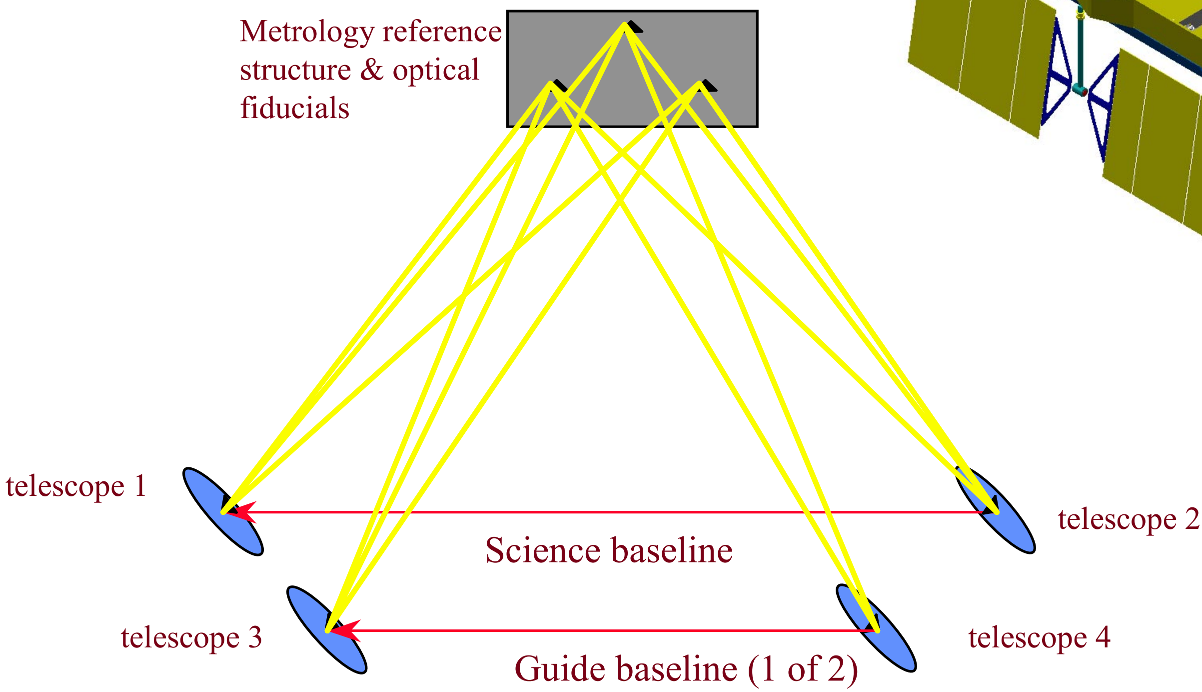


Guide interferometers measure the attitude (orientation) of the interferometer wrt “guide” stars.

For purely geometric reasons the best location for the guide stars is at the extreme of the field of regard (perpendicular to the baseline)

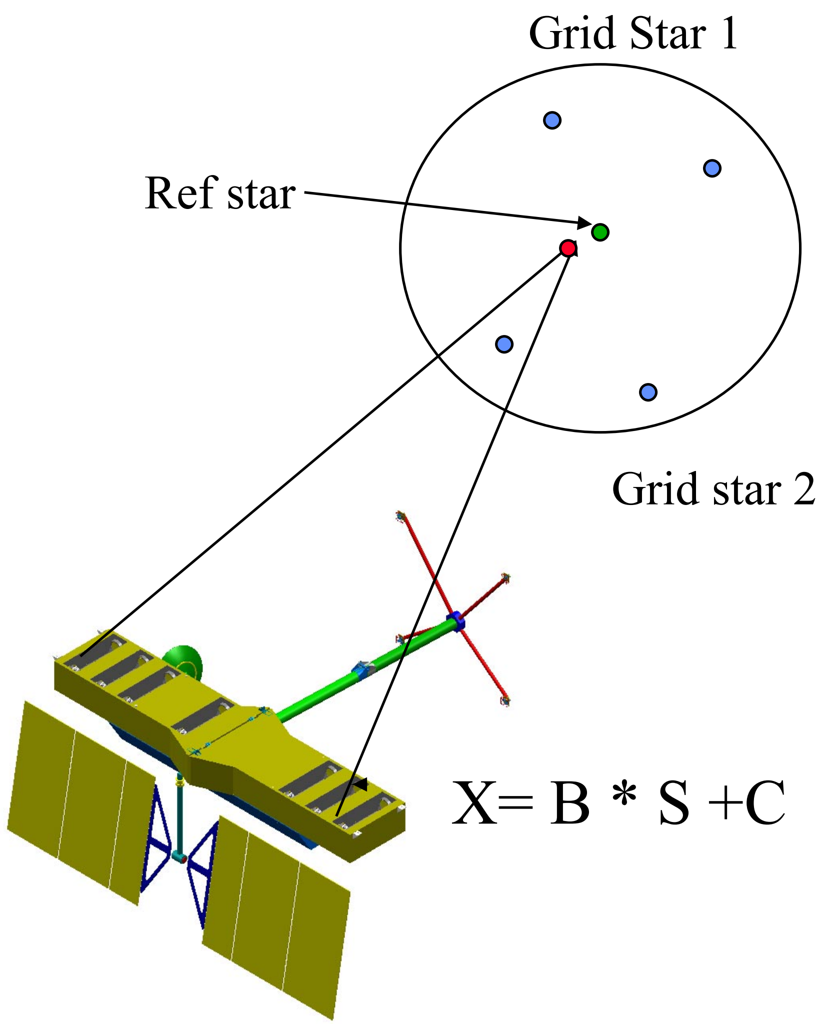
External Metrology





The external metrology system "ties" the guide interferometer to the science interferometer, at the picometer level

Baseline Determination in Space (3)



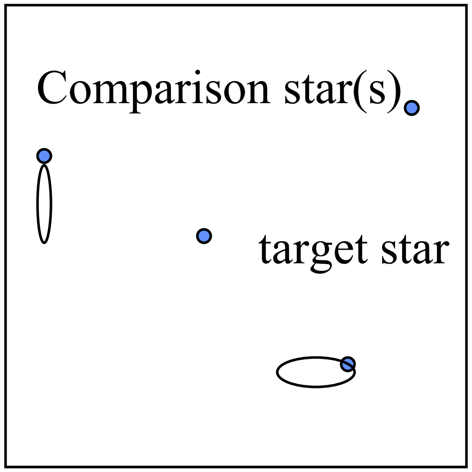
With the baseline stabilized (using the guide stars)
The science interferometer observses a number (4~6) “grid stars”

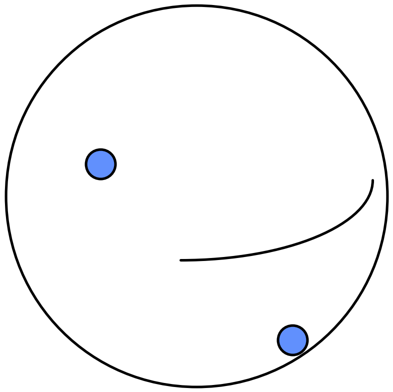
The SIM mission will pick ~3000 grid stars over the sky whose positions at the end of the mission will be known to ~4 uas.

These stars are used to measure the baseline orientation to ~ 60uas (3nm)
The ref star is used to measure the delay offset (C) to ~ 50pm

Astrophysical Issues

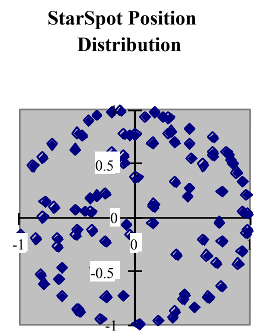
- *All stars (including references) have companions*
  - *Use the fact that a planet around A does not influence B-C separation*
- *Star spots*
  - *A Solar type star @ 10pc will show spot noise ~1 uas*
  - *Use multi-color astrometry and make use of the fact that the spots are much "darker" at short (blue) wavelengths.*
    - *Use multi-color observations to extrapolate correct for spots.*

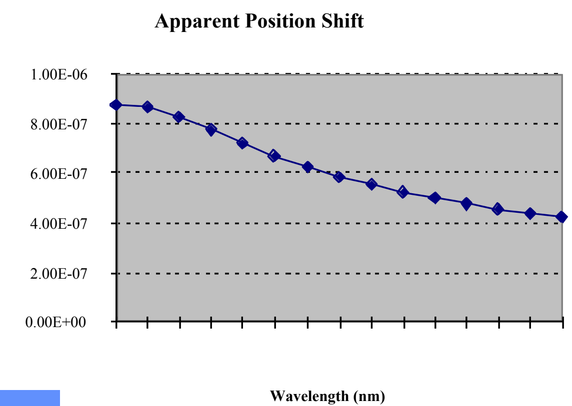




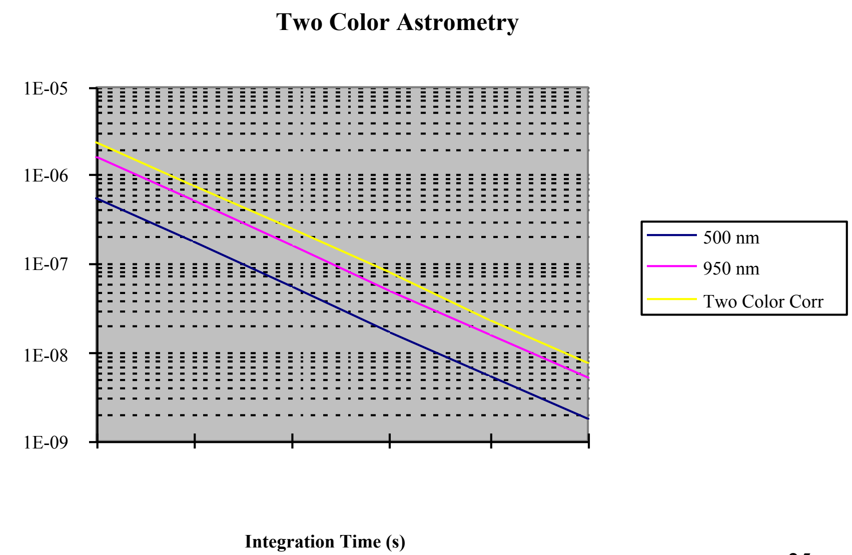
Star Spots/Multi-Color Astrometry

- *A Single Sunspot (0.04% Area) can Change the Apparent Position of the Sun by 0.1 µas Viewed From 10 pc -- 100 Spots Create an ~1 µas Effect.*
- *The Center of Light is a Function of Wavelength, So Measurements at Multiple Wavelengths Can Be Used to Estimate the Effect.*
- *SIM Uses Multicolor Astrometry to Correct the Star Position Estimate.*



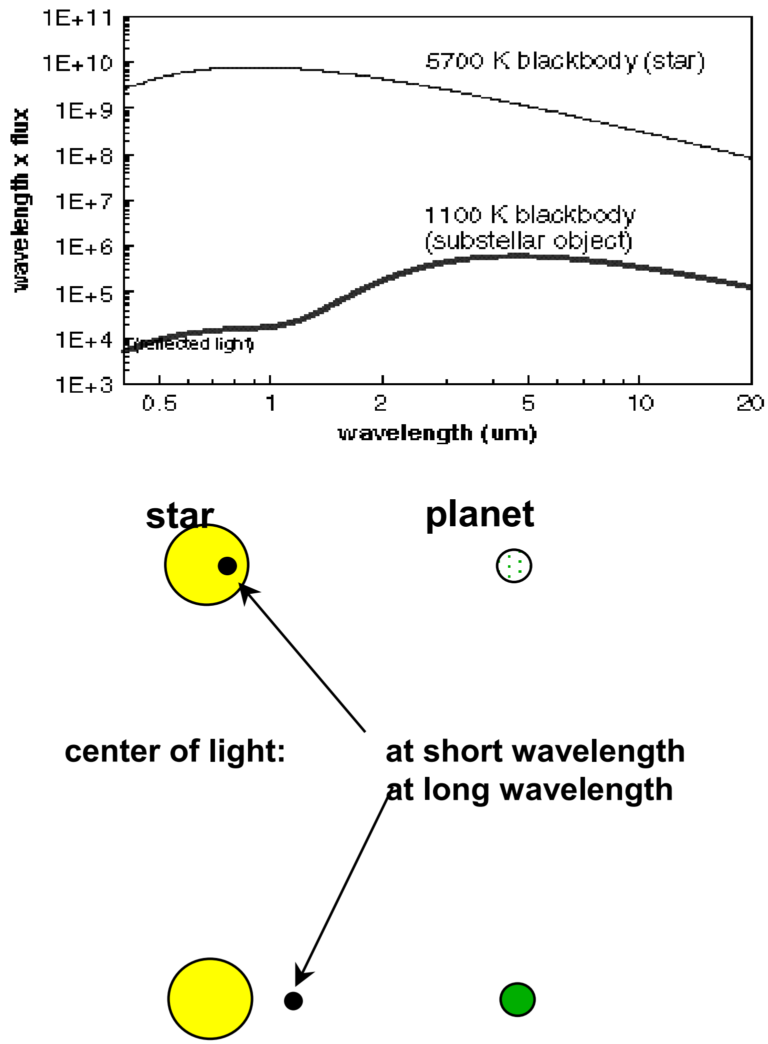


G2V Spectral Type @ 10 pc
100 Sun-type Spots in Randomly Chosen Pattern

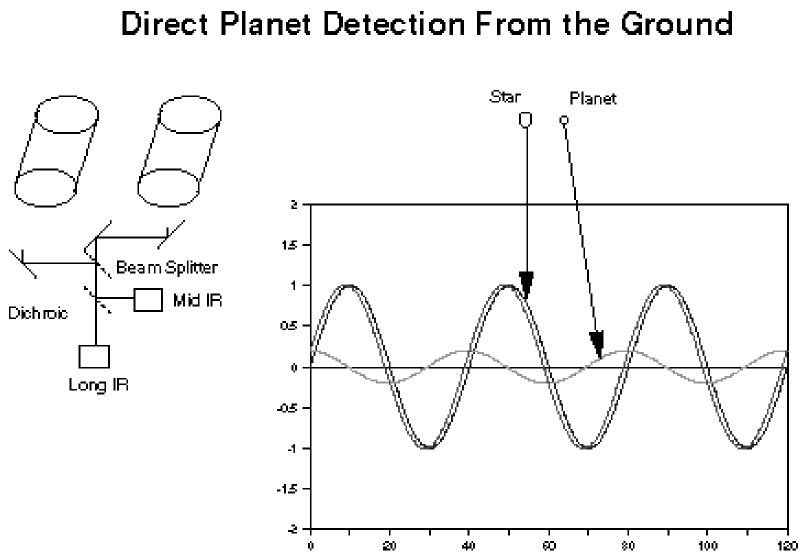


Photocenter motion of Star-Planets Direct Detection of Hot Jupiters

- *Jupiter sized objects at temperatures of 500K to 1300K can be detected from the ground by their IR emission*
- *The basic idea is 2 color phase reference interferometry which makes use of the different BB spectra of the planet and star*



Astrometry of the Photocenter



Phase Difference Interferometry for Planet Detection

viewgraph made in 1990

Size of effect
Assume star-planet sep 4mas
star-planet flux ratio 10^4

Photocenter displacement
0.4 uas

Imaging from phase difference data

- *The phase difference between the two colors changes as the earth rotates, and the fringes of the star and planet move with respect to each other.*
- *Phase vs baseline orientation and length can be "inverted" to produce an image of the planet.*